K/Ka-Band Aeronautical Experiments

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ABSTRACT

This paper discusses a series of aeronautical experiments that utilize the Advanced Communicant ion Technology Satellite (AC-I'S) Broadband Aeronautical Terminal (BAT) [1]. These experiments were designed to explore the uses of K- and Ka-band for aeronautical applications. Planned experiments are also discussed.

INTRODUCTION

A natural extension of the ACTS land-mobile experiments was to investigate the aeronautical K/Ka-band communications channel. The BAT operates at higher data rates than the land-mobile terminal, and demonstrates and characterizes the performance of high data rate aeronautical Ka-band communications [2]. The experiments performed with the BAT are described in this paper.

EXPERIMENTS

The BAT is designed to explore the use of K/Ka-band for high data rate aeronautical satellite communications. The broadband terminal, used in conjunction with the ACTS mechanically steerable antenna, can achieve data rates of 2 megabits per second. The aeronautical terminal is being utilized to test a variety of applications that require a high data rate communications link.

Experimentation with the BAT requires ACTS to be operated in the bent-pipe mode. The ACTS LA/San Diego spot beam is used to establish the communication link between ACTS and the fixed terminal at JPL in Pasadena, CA. The ACTS mechanically steerable dish antenna is used to establish the link between ACTS and the aircraft. Use of the ACTS steerable antenna introduces the additional complication of requiring the antenna to continuously track the aircraft. The ACTS steerable antenna has a 3 dB contour diameter of 280 miles, wh ich coupled with a maximum aircraft ground speed of 700 mph, results in a low dynamic tracking requirement. This tracking is accomplished by multiplexing aircraft positioning information (GPS latitude and longitude) with the data stream transmitted from the aircraft to the fixed terminal located at JPL. At the fixed terminal the positioning information is then demultiplexed and transmitted via the public switched telephone network (PSTN) to the ACTS control station, located in Cleveland, Ohio, where the ACTS is then commanded to point the steerable antenna to the aircraft location.

Three sets of experiments/demonstrations are described in the remainder of this section.

Kuiper A irborne Observatory Live Television Broadcast

[bring the summer of 1995 the I] Al' was installed on NASA's Kuiper Airborne Observatory (KAO), a C-14 *I* A jet transport aircraft which carries a 0.9-meter reflecting telescope used for in frared astronomy. Four experiments using the ACTS were carried out from the KAO in flight: I) "Live From the Stratosphere", a multi-media educational program which included live video/audio broadcasts on U.S. PBS and NASA TV, and a wide spectrum of Internet activities, 2) a video teleconferencebetween the KAO and several hundred people at the San Francisco Exploratorium, called "I,ive Interactive Network to Knowledge" (Project LINK), 3) "telescience", i.e. control of science instrumentation on the KAO from the ground during data flights, and 4) telescope-system health monitoring from the ground during flights. Figure I shows the KAO and Figure 2 shows the KAO with the antenna and radome installed.

Figure I Kuiper Airborne Observatory(KAO)C-141

Figure 2 BAT Antenna and Radome installed on KAO

The configuration for the KAO experiment is shown in Figure 3. As indicated in this figure the aircraft transmitted a combination of video, audio, and Internet data via ACTS to the JPL fixed station. The fixed station relayed this information via terrestrial 1’1 line to NASA Ames where worldwide Internet connectivity was established, and the audio and video were transmitted via commercial satellite to Public Broadcasting System (PBS) stations in Maryland and New York who incorporated tbcm into live broadcasts. Similar data traveled on the return path from the fixed station to the aircraft. The fear components of this experiment arc discussed below.

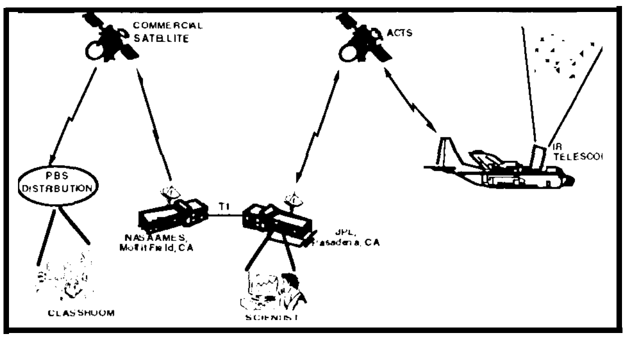

Figure 3 KAO Experiment Configuration

Live From the Stratosphere was the second of three programs in the Passport to Knowledge series, a multi-media educational program designed to take students on “electronic field trips” into the world of scientific discovery. The Passport to Knowledge series seeks to integrate various communications media into a hands-on, interactive educational experience for teachers and students.

Live From the Stratosphere activities centered on two KAO flights on October 12 and 13, 1995. During these flights, two-way video, audio, and data were transmitted, via ACTS, between the KAO and the ground. The video and audio were sent via a combination of land lines and commercial satellites to public ‘1’V stations on the East coast, where the program was produced and sent oat live for broadcast on PBS channels and NASA TV. Sixty percent of PBS stations around the country broadcast some part of *Live From the Stratosphere*.

During the *Live From the Stratosphere* program, select "uplink" sites at museums and schools were given the opportunity to communicate directly with the crew and scientists aboard the KAO. Students and teachers interviewed the crew and scientists, and participated in on-line activities relating to the KAO flights. For example, students plotted the track of the aircraft on maps, using latitude, longitude and heading data that was transmitted over Internet at regular time intervals daring the flights. One group of students at the Adler Planetarium in Chicago was able to control the KAO’S telescope via the Internet from their computer. A scientist on-board the KAO controlled and obtained data from a telescope in New Mexico, designed for remote control.

I’here were 1300 email subscriptions to *Live From the Stratosphere*, and approximately 100 teachers participated in on-line discussions. There were tens of thousands of visitors on the Web site, and fifty KAO experts responded to about 250 email questions from chi ldren.

Project I,/A’K: During two KAO research flights in September 1995, teachers and students aboard the KAO conducted "CUSeeMe" teleconferencing across the Internet with an audience of hundreds at the San Francisco Exploratorium. During the flights, educational demonstrations relating to astronomy and to the aircraft environment were conducted. People on the aircraft communicated with the audience at the Exploratorium via Internet teleconferencing and airphone. The excitement and enthusiasm of the crowd at the Exploratorium was tremendous, as kids had the opportunity to interact in real-time with people aboard the KAO.

Remote Observing: During research flights in September, and daring the Live From the Stratosphere flights in October, scientists from the University of Chicago’s Yerkes Observatory demonstrated remote control of systems on the aircraft via the ACTS communications link. Activities included control of the telescope system, transmittal of science and telescope data between the aircraft and the ground, and "CUSeeMe" teleconferencing with audio and video capability. in addition, a telescope in New Mexico was operated from the KAO in flight.

Real-time Automated Diagnosis System (RAD): The RAD is a failure monitoring system that receives data from KAO telescope subsystems and ases the data to diagnose and report system problems to an operator on the ground. Communication was over the Internet, via the ACTS link, daring KAO research flights in August, 1995. The purpose of this experiment was to demonstrate the feasibility of using an automated diagnosis system for the airborne telescope, and to demonstrate the possibilities that the RAD may provide for monitoring and diagnosing telescope problems from the ground.

The Broadband Aeronautical Terminal was successfully installed on the KAO C-14 I aircraft shown in Figure 1. A total of 150 boars of in-flight operation of the terminal daring a fear month test period were performed and the term inal was found to perform quite well daring these tests. The system was able to acquire the satellite signal prior to take-off and remain locked daring take-off, cruise, and landing, maintaining a full-duplex compressed video link. Measurements of signal-to-noise ratio for the signal received in the aircraft and at the fixed terminal indicate that the terminal performance is better than predicted by the link budgets, and a fall-duplex T1 data rate (1 .544 Mbps) could be supported.

The flight plan for a KAO test flight on August 26, 1995 is shown in Figure 4. The flight originated in Moffett Field, CA, position 1, proceeded to position 2 and so on until returning to Moffett Field after passing through position 15. An example of the data recorded daring this flight over the Western United States is provided in Figure 5. This plot shows the received pilot power level in the aircraft of a pilot signal that is transmitted from the JPL fixed terminal via ACTS to the aircraft. The received pilot power level is shown daring a two minute long aircraft turn in which the beading changes by 330° and the roll angle changes by -30°. The received pilot power indicates that the antenna maintained tracking daring this steep roll angle change. The plot also indicates that there is signal variation ofap to 0.7 dB daring the tarn (+/- 0.5 dB RMS for the entire data set), and as a result the antenna tracking algorithm parameters were adjusted to improve this performance for subsequent flights. Figure 6 contains freeze frames of the live compressed video that was transmitted from the in-flight KAO to the JPL fixed terminal from 41,000 feet, The frames show a scientist taking measurements with the telescope.

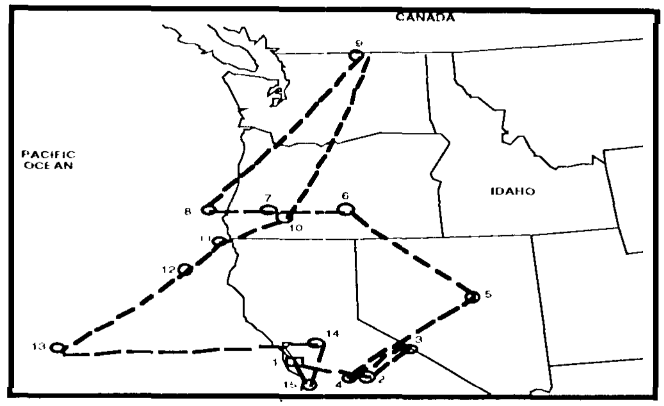

Figure 4 KAO Flight Plan August 26, 1995

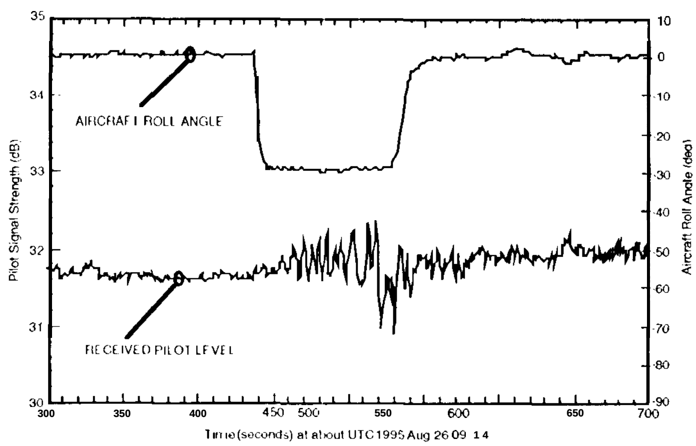

Figure 5 Flight Performance Data for KAO

Figure 6 In-flight Video Transmitted from the KAO to JPL Fixed Terminal

The experiments carried out from the KAO using ACTS will serve as proof-of-concept for development of future satellite communication capabilities for airborne astronomy on the KAO or its planned successor, the Stratospheric Observatory For Infrared Astronomy (SOFIA).

Both the KAO and SOFIA projects are committed to hands-on educational programs which get teachers and students directly involved with science activities. The Live From the Stratosphere and Exploratorium experiments demonstrated satellite based communications capabilities for involving larger numbers of participants in research flights, via video/audio broadcasts, teleconferencing, and other Internet activities, than is currently possible due to seating and other limitations.

Results from the RAD experiment may be used in developing similar capabilities for the KAO or SOFIA. Development of a remote system health monitoring and diagnosis capability via satellite communications may allow a reduction in the number of crew members needed on board the aircraft for research flights, which is a goal for both programs.

Remote observing capabilities would open up new possibilities for scientists involved in airborne astronomy. Scientists could participate in KAO or SOFIA research flights without having to be present on the aircraft. In addition to lowering the number of people on board the aircraft, and lowering travel time and costs for the scientists, this feature would be useful to those scientists who cannot fly due to health reasons. Having immediate access to science data from the aircraft may also be helpful for time-critical events, such as the Jupiter-comet collisions that occurred in July 1994, or occultation events where world-wide coordination of science results in real-time may be important.

Rockwell International Aeronautical High Data Rate Experiments

Rockwell International flew an ACTS experiment to characterize the high speed data performance available to/from a turbojet aircraft, and more specifically a small business jet. The motivation in undertaking this experiment was several fold:

- The demand for higher data rates to/from aircraft continues to climb, and presently exceeds the technical capability to provide it. Imagery downlinks constitute most of that demand.
- Government users are primarily concerned with sensor downlinks demanding wide digital bandwidth, plus the ability to upload large databases quickly.
- The commercial airline market wants significant "office-in-the-sky" bandwidth into which multiple two-way digital signals may be multiplexed (e.g., voice, fax, data, etc.) Only limited use is foreseen for video entertainment.

As a supplier to both markets, Rockwell recognizes the potential for Ka-band service to satisfy these needs, and has undertaken an effort to establish a performance baseline to support further commercialization of Ka-band services.

The configuration for the Rockwell experiment is shown in Figure 7. As indicated in this figure the aircraft transmitted a combination of video, audio, and sensor data via ACTS to the JPL fixed station. Similar data traveled on the return path from the fixed station to the aircraft. The configuration details of this experiment are discussed below.

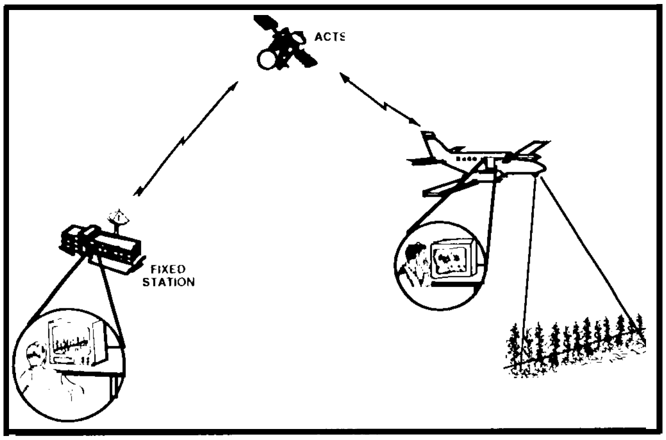

Figure 7 Rockwell Experiment Configuration

Experimental Equipment Configuration: The Rockwell experiment utilized one of the company's Saberliner jet aircraft, and more specifically the aircraft used for engineering and FAA qualification testing of various avionics. The aircraft antenna was mounted on an existing reinforced port of the aircraft approximately over the wing and just slightly off centerline. The antenna was designed to have minimal protrusion, and hence protrudes through the pressure hull adapter into the headroom of the cabin only a few inches. Careful analysis was done by Saberliner Inc. to determine the aerodynamic impact of the radome on aircraft safety and performance, and concluded that the top speed of the aircraft has to be reduced with the antenna mounted. Installation of the antenna was done by Saberliner Inc. in August 1995 and is shown in Figure 8.

Figure 8 Rockwell Saberliner with BAT Antenna and Radome Installed

The equipment configuration installed in the aircraft by Rockwell's Flight Applications Engineering shop includes the basic JPL BAT: RF converter and waveguide, IF converter, TWT power amplifier, Modem, Video Codec, Antenna control unit, Data logger, and test equipment.

Navigation data is supplied to the antenna controller from the aircraft bus for antenna pointing, and relayed to the laptop for logging and uplinking. The equipment is mounted in a 19 inch rack pallet, which is fastened to the seat tracks in place of a passenger seat.

Flight Tests: The Saberliner flew the test missions in two sessions: August 1995 and March 1996. The tests were deliberately split to allow testing in the humid summer weather and dry winter weather of the midwestern United States. The broad goals of the testing were to characterize link performance as a function of aircraft motion/antenna pointing as well as ambient weather conditions. This was done at a variety of data rates. While precipitation attenuation is a well-known phenomenon on tbc ground, little detailed data is available on the airborne effects and hence this was a primary objective of this experiment.

To characterize the precipitation conditions, data from the onboard Rockwell weather data together with NEXRAD weather radar data were collected to characterize the precipitation and humidity conditions in the path between the aircraft and satellite. The aircraft flight schedule and coarse were set to obtain the desired weather conditions.

The final series of tests utilized a "live" television camera in the cockpit window downlinked to the ground via a video codec, replacing the digital test pattern used for the preceding tests. The complete data set for the flight test series is being analyzed to establish the link performance patterns to guide system and equipment design for the next generation of airborne Ka-band capability [3].

Flight tests found the terminal to perform quite well. The system was able to acquire the satellite signal prior to take-off and remain locked daring take-off, cruise, and landing, maintaining a full-duplex data link the entire time. During these flights that used a 10 W TWTA and the ACTS steerable antenna in a fixed point mode, fall duplex links of 64 kbps were established between the Saberliner flying in the Iowa/Nebraska/South Dakota area and the fixed terminal at JPL. Good signal-to-noise ratios were maintained for a variety of aircraft maneuvers and varying weather conditions in both the summer and the winter.

Figures 9 and 10 show a sampling of the flight test data that was recorded daring the Rockwell experiments. Figure 9 covers a period when the aircraft was taxiing on the ground prior to take-off and the subsequent climb to an elevation of 30,000 feet. The parameters displayed include the pitch, roll, yaw, and altitude of the aircraft, the azimuth and elevation angles of the antenna relative to the aircraft, and the aircraft's received pilot signal-to-noise ratio. A point of interest is the pilot SNR which is displayed as a voltage ratio. When this scale is converted to d[l-power the maximum peak-to-peak variation is found to be less than 1.5 dB. This indicates that the aeronautical antenna was able to consistently track in both azimuth and elevation and receive the transmitted signal uninterrupted for a variety of aircraft maneuvers on the ground and while climbing to altitude. Figure IO shows the same parameters for the level flight phase following immediately after the climb to altitude. This plot again shows that the maximum peak-to-peak variation is 1.5 dB as the antenna tracks through various pitch, roll, and yaw perturbations.

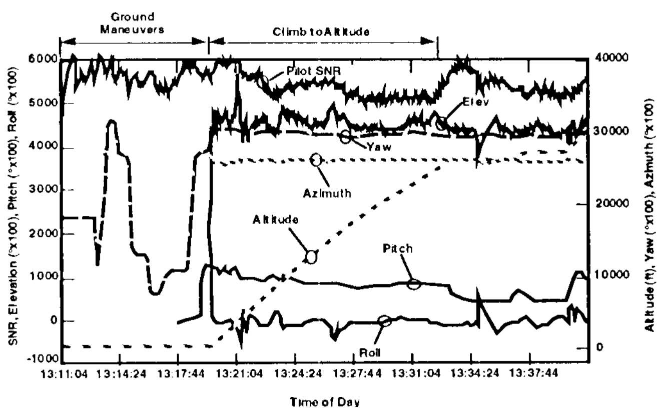

Figure 9 Rockwell Saberliner Flight Test Data for Take-off and Climb to Altitude

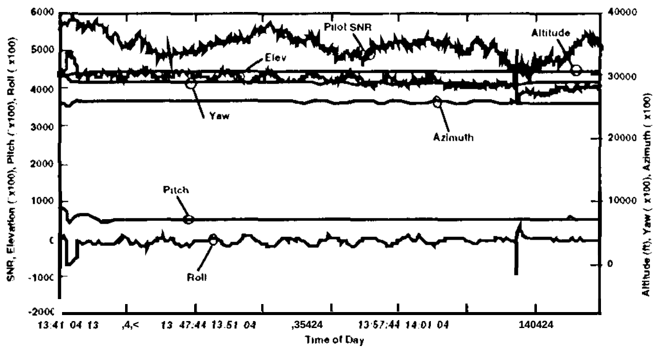

Figure 10 Rockwell Saberliner F'light Test Data for Level Flight

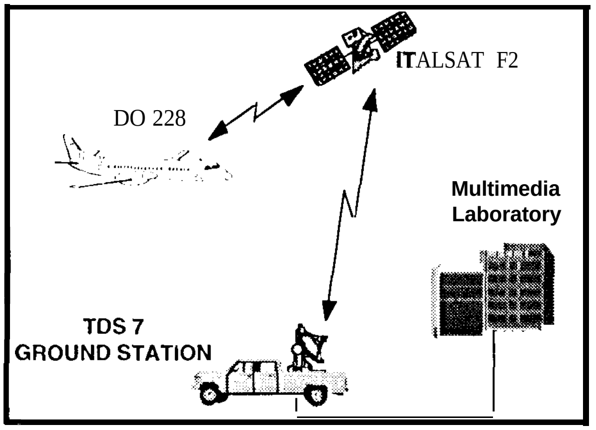

Figure 11 ABATE Experiment Configuration.

ABATE

Early in 1998, components of the BAT will be used to support flight trials as part of the European Space Agency's (ESA) Advanced Communications Technology and Services (ACT'S) project, specifically the ACTS Broadband Aeronautical Terminal Experiment (ABATE). The ABATE project will assess technologies, leading to definition of a future, advanced aeronautical mobile satellite system operating in the K/Ka bands and capable of providing broadband telecommunications services as **well** as classical services associated with current low bit rate technologies.

Two sets of flight trials are planned but, the BAT equipment will only be used during the second set. Tbe first set of flight trials will take place in the fall of 1997 and will not utilize the JPL equipment. During those trials, the aircraft will be equipped with a receive only system to make channel measurements and test different antenna pointing techniques. Deutsche Forschungsanstalt fur Luft und Raumfahrt CV (DLR) will modify their land mobile antenna and RF equipment for this phase of flight trials.

The second set of flight trials will be conducted in March 1998. The experimental configuration is shown in Figure 11. '1'best flights will serve to demonstrate a full duplex audio/video/internct capability between the aircraft and tbc multimedia laboratory in Rome, Italy via tbc ITALSAT satellite. The JPL equipment (i.e., BAT antenna, RF and IF converters, support equipment) will be used during this phase of the flight trials to provide a transmit and receive capability onboard the aircraft. During these trials, channel measurements (e.g., BER, Eb/No, received power, pilot power) wi II be made.

Four to six flights, each of about four hours duration, will be performed. The same aircraft, DLR's DO-228 turboprop, will be used for all flight trials. It is expected that the plane will fly out of Ciampino, a military airbase south of Rome.

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